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Laboratory characterization of cementitiously treated/stabilized very weak subgrade soil under cyclic loading

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Abstract

This research study was performed to examine the appropriate treatment/stabilization schemes for very weak subgrade soils at high water contents, and to evaluate the corresponding performance-related properties [e.g., resilient modulus and permanent deformation] for use in the design and analysis of pavement structures. Five different soil types, that represent the typical range in subgrade soils in Louisiana, were collected and considered in this study. Three different moisture contents (at the wet side of optimum), producing a raw soil strength of 172 kPa (25 psi) or less, were selected for treatment/stabilization. The percentage of cementitious stabilizer (lime or cement) was determined to achieve a target 7-day strength value of 345 kPa (50 psi), as treatment for working table applications, and 1034 kPa (150 psi), as stabilization for subbase applications. Repeated load triaxial (RLT) tests were performed on the laboratory-molded treated/stabilized specimens in order to evaluate their resilient modulus and to study their deformation behavior under cyclic loading. A good correlation was observed between the water/cement ratio and both the resilient modulus and the permanent deformation of the specimens. The soil specimens were compacted at low water/cement ratios and showed better performances than those compacted at high water/cement ratios. The test results also showed that the use of a direct correlation between the unconfined compressive strength (UCS) and the resilient modulus for cementitiously stabilized soil can be misleading. In the case of heavily treated/stabilized subgrade soils for subbase applications, the permanent deformation of this layer can be ignored in pavement design.

Keywords: Cementitiously treated/stabilized soil; Weak subgrade; Repeated load triaxial test; Resilient modulus; Permanent deformation

1. Introduction

Subgrade is the lowest supporting layer in the pavement structure underlying the base layer. Generally, the subgrade consists of locally available soil deposits that sometimes might be very soft and/or very wet and do not have enough strength/stiffness to support the pavement's traffic loading. The replacement of such soil with better quality borrow soil fill is not always a good option, especially in pavement construction, due to the associated extra costs of the excavation and the hauling of the materials. The use of cementitious materials to treat/stabilize poor subgrade is a widely accepted practice by many state highway agencies. A well-engineered and constructed cementitiously treated/stabilized subgrade layer usually requires achieving a threshold compressive strength that is capable of providing strong and durable support to construction loading and pavement structures. This treated/stabilized layer can be incorporated into the structural design of pavements by increasing the modulus of the composite subgrade layer and considering it as a separate subbase layer.

The soil stabilization mechanism depends on the type of applied stabilizer; it may vary from the formation of new compounds,

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binding the finer soil particles, to a coating particle surface by the stabilizer to limit the moisture sensitivity (Little and Nair, 2009). The overall stabilization/treated process in the presence of water can be summarized into four different processes: cation exchange, flocculation and agglomeration, cementitious hydration, and pozzolanic reaction (Prusinski and Bhattacharja, 1999; Mallela et al., 2004). Portland cement and lime are both calcium-based products; however, their differences may include important properties such as strength, time-dependency on the strength development, curing, and the durability and performance of the treatment (Prusinski and Bhattacharja, 1999). In the case of cement-treated/stabilized soils, all four aforementioned processes will occur, whereas in the case of lime-treated/stabilized soils, cementitious hydration will be absent.

For soil–lime mixtures, cation exchange and flocculation–agglomeration are the primary reactions which take place immediately after mixing. During these reactions, the divalent calcium ions, supplied by the lime, replace the monovalent cations that are generally associated with clay minerals. These reactions bring about immediate changes in texture, plasticity, and workability because the exchange of cations causes a reduction in the size of the diffused double water layer, thereby allowing clay particles to clump together into large-sized aggregates. The pozzolanic reaction process is a long and slow process. It occurs between the lime and the silica and alumina of the clay mineral and produces cementitious materials such as calcium–silicate–hydrates and calcium–alumina–hydrates. Studies have shown that when the pH of the soil increases to 12.4, which is the pH of saturated lime water, the solubility of the silica and the alumina increase significantly (Muhunthan and Sariosseiri, 2008). Therefore, as long as enough calcium from the lime remains in the mixture and the pH remains at least at 12.4, the pozzolanic reaction will continue to occur. The basic pozzolanic reactions are described in the following equations:

$$Ca(OH)_2 + SiO_2 \rightarrow CaO \cdot SiO_2 \cdot H_2O \text{ (C–S–H)} \quad (1)$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow CaO \cdot Al_2O_3 \cdot H_2O \text{ (C–A–H)} \quad (2)$$

Portland cement is comprised of calcium–silicates and calcium–aluminates that hydrate to produce cementitious materials, which bind the soil particles together. For soil–cement mixtures, the hydration of cement is the most important contributor to the improvement of the engineering properties of soil (Pendola et al., 1969). Cement hydration is relatively fast and causes an immediate gain in the strength of the soil. The hydration behavior of calcium–silicates in cement can be described by the following equations, while the hydration of calcium–aluminates is somewhat more complex:

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3\ CaO \cdot 2SiO_2 \cdot 4H_2O \text{ (C–S–H)} + 3\ Ca(OH)_2 \quad (3)$$

$$2Ca_2SiO_4 + 5H_2O \rightarrow 3\ CaO \cdot 2SiO_2 \cdot 4H_2O \text{ (C–S–H)} + Ca(OH)_2 \quad (4)$$

Much of the tricalcium silicate (Ca_3SiO_5) hydration occurs during the first few days, leading to substantial gains in strength. The dicalcium silicate (Ca_2SiO_4) hydration contributes little to the early strength of cement soil, but makes substantial contributions to the strength of mature cement paste. Similar to soil–lime mixtures, the cation exchange and flocculation–agglomeration also take place immediately after the soil and the cement are mixed, resulting in a reduction in soil plasticity. The lime generated during the hydration of the cement helps increase the binding between the soil particles through the pozzolanic reactions.

A lot of factors have been identified in the literature as having an effect on the stiffness (or resilient modulus) of cementitiously stabilized soils. These factors include the curing time, the deviatoric stress, the moisture content, the porosity-cement ratio, the curing temperature, the percentage and type of stabilizer, the soil properties, the density, and the delay time in compaction (e.g., Puppala et al., 1996; Achampong et al., 1997; Solanki et al., 2009; Consoli et al., 2011; Taheri and Tatsuoka, 2012). In general, the resilient modulus of the treated/stabilized subgrade soils increases with an increase in stabilizer content under an identical moisture content, while the permanent deformation of the treated/stabilized subgrade soils decreases with an increase in stabilizer content (Puppala et al., 1996; Achampong et al., 1997; Mohammad and Saadeh, 2008; Ling et al., 2008; Solanki et al., 2010). Several studies in the literature have shown a strong double logarithmic linear relationship between the resilient modulus and the curing time for lime/cement-stabilized soils (e.g., Ling et al., 2008; Chen and Abu-Farsakh, 2010). Generally, lime- and lime/fly ash-stabilized soils cure much more slowly than cement-stabilized soils (Little, 1999). The stress state (deviatoric stress and confining pressure) at which the resilient modulus should be estimated can be determined, in general, from a structural analysis of the trial design (after properly accounting for overburden pressure) (ARA, 2004). The correlations between the resilient modulus and the unconfined compressive strength (UCS) for stabilized layers have also been studied and proposed by several researchers (Thompson, 1966, 1986; Little et al., 1994). Some of these correlations are recommended by the Mechanistic-Empirical Pavement Design Guide (MEPDG) for determining the resilient modulus of stabilized soil for Level 2 designs (ARA, 2004).

In many cases, the subgrade soils in Louisiana have in-situ moisture contents that are much higher than the optimum value. Therefore, the predictions of the subgrade behavior, based on the soil properties determined at or near the optimum moisture content, are not rationale. Since most of the available studies on the evaluation of treated/stabilized subgrade soils are focused on evaluating the performance of subgrades compacted at or near optimum moisture contents, this research will focus on evaluating the behavior of treating/stabilizing very weak subgrade soils having moisture contents way beyond the soils' optimum moisture contents, even sometimes reaching up to the liquid limit of the soil, in order to cope with the in-situ worst scenario of pavement/foundation construction in Louisiana. Two levels of target UCS values will be selected: (a) to represent the construction of a working table [minimum 7-day strength of 345 kPa (50 psi)] and (b) to represent the construction of a subbase layer [minimum 7-day strength of 1034 kPa (150 psi], as recommended in a previous study conducted on Louisiana soils (Gautreau et al., 2010). The behavior of the laboratory-molded specimens will be observed under repeated load triaxial (RLT) tests in the form of resilient modulus tests and permanent deformation tests.

2. Material properties and test program

2.1. Material properties

Five types of subgrade soils with different plasticity levels (from low PI to very high PI) were selected for this study. A series of physical property tests were carried out to characterize these soils. They include the liquid limit, the plastic limit, the grain size distribution, and Standard Proctor compaction. The results of these tests and the corresponding soil classifications are presented in Table 1.

2.2. Testing setup

All RLT tests were carried out using the Material Testing System (MTS810) with a closed loop and servo hydraulic system. Fig. 1 shows a photo of the testing equipment. The applied loads were measured using a load cell. The axial deformation was measured using two Linearly Variable Differential Transducers (LVDTs). The two LVDTs were secured to the top plate. The confining pressure was achieved through the use of pressurized air. It was measured using a pressure sensor. The prepared sample was placed on the load cell and secured to the cell through a base plate (Fig. 1). The sample was then sealed with o-rings and clamps so that confining pressure could be applied. Once the sample was safely secured inside the pressure chamber, it was first conditioned to be prepared for the RLT tests.

2.3. Sample preparation

All the samples were molded in a mold having a height of 142 mm (5.6 in.) and a diameter of 71 mm (2.8 in.). All the samples were compacted in five layers, with 9 blows per layer, to achieve a uniform density. The selected number of layers is consistent with AASHTO T-307 for the resilient modulus testing of cohesive soils. The number of blows per layer was determined by applying the same energy used in Standard Proctor tests (600 kN-m/m^3), to compact five layers of soils in a mold with a diameter of 71 mm (2.8 in.) and a height of 142 mm (5.6 in.), while keeping the hammer weight as well as the drop height constant.

The molded samples were placed in an airtight plastic wrapper and kept in a 100% humid room in accordance with the ASTM standard procedure (ASTM D 1632). ASTM D-2166-06, ASTM D 5102-09, and ASTM D 1633-00 were followed to compact and test the raw, lime, and cement-treated/stabilized soils, respectively. After a curing period of 7 or 28 days, the soil samples were removed from the plastic wrapper. The cement-treated/stabilized samples were then submerged in a water bath for approximately 3 to 4 h (ASTM D 1633-00) prior to testing. The lime-treated/stabilized soils, on the other hand, were kept above porous stone for capillarity suction for about 8 to 10 h prior to testing.

2.4. Testing program

2.4.1. Unconfined compressive strength (UCS) tests

The UCS of the tested specimens was determined in accordance with the ASTM D 2166-06 test method, which consists of applying a load to produce an axial strain at a rate of 1% of the total height of each specimen. UCS tests were first performed on the raw soils at different moisture contents to establish the UCS-moisture content relationship. Three moisture contents, at the wet side of optimum producing UCS of 172 kPa (25 psi) or less, were then selected to simulate the very weak wet soil conditions in the field. The UCS tests were then also conducted

Fig. 1. Testing setup.

Table 1
Properties of soils used in the study.

Soil no.	Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI (%)	AASTHO classification	USCS classification	MDD* (kg/m^3)	OMC* (%)
I	58.3	30.7	11.0	23	15	8	A-4	CL	1940	11.5
II	15.6	62.4	22.0	33	19	14	A-6	CL	1727	18.0
III	20.0	63.0	17.0	40	12	28	A-6	CL	1744	15.6
IV	9.7	49.0	41.0	61	18	43	A-7-6	CH	1642	22.1
V	1.6	26.4	72.0	96	29	67	A-7-6	CH	1406	25.7

Note: LL: liquid limit, PL: plastic limit, PI: plastic index, MDD: maximum dry density, OMC: optimum moisture content.

on the treated/stabilized soils to evaluate the suitability of the particular stabilizer for a particular soil and to determine the percentage of stabilizer needed to achieve the target 7-day strength values of 345 kPa (50 psi) for working table applications and 1034 kPa (150 psi) for the stabilization of the subbase. The UCS tests on untreated soil specimens were conducted immediately after compaction, whereas the treated/stabilized soil specimens were cured in a humid room for 7 days or 28 days prior to testing.

2.4.2. Repeated load triaxial (RLT) tests

In order to characterize the resilient and permanent deformation behavior of the treated/stabilized very weak wet subgrade soils, RLT tests were performed to determine the resilient modulus (M_r) and the single-stage permanent deformation characteristics of the specimens. The RLT tests were conducted by applying a repeated axial cyclic stress of a fixed magnitude, load duration, and cycle duration to a cylindrical test specimen for a certain number of cycles. While the specimen was subject to this dynamic cyclic stress, it was also subjected to a static confining pressure. The cyclic loading in this study consists of repeated cycles of a haversine-shaped load pulse, as shown in Fig. 2a. These load pulses consist of a 0.1-s load duration and a 0.9-s rest period.

For resilient modulus tests, the RLT tests were performed in accordance with the AASHTO-T307 standard method for determining the resilient modulus of subgrade soils (AASHTO, 2003). In this test method, the samples are first conditioned by applying 1000 load cycles with a cyclic stress of 24.8 kPa and a confining stress of 41.4 kPa. The conditioning step removes most irregularities from the top and bottom surfaces of the test sample and also suppresses most of the initial stage of permanent deformation. This step is followed by a sequence of loading with various confining and cyclic stresses. The confining pressure is first set at 41.4 kPa, and the cyclic stress is increased from 12.4 kPa to 24.8 kPa, then to 37.2 kPa, then to 49.6 kPa, and finally to 62.1 kPa, with 100 cycles for each load combination. Subsequently, the confining pressure is decreased to 27.6 kPa and then to 13.8 kPa. The cyclic stress varies in the same way as with the confining pressure of 41.4 kPa. The resilient modulus is defined as the ratio of the cyclic stress to the recoverable or resilient strain, as shown in Fig. 2b (Eq. (1)). The resilient modulus tests were performed on laboratory-molded samples that were cured for 7 days and 28 days prior to testing. It was not possible to conduct resilient modulus tests on the raw soil specimens at high moisture contents, since they were too weak to sustain the RLT tests.

$$M_r = \frac{\sigma_{cyc}}{\varepsilon_r} \tag{5}$$

For single-stage permanent deformation tests, the samples are first conditioned by applying a cyclic stress of 15.5 kPa and a confining stress of 41.4 kPa for 1000 cycles. Once the conditioning phase is completed, the confining pressure is set as 13.8 kPa. A cyclic stress of 37.2 kPa is then applied to the specimen for 100,000 cycles. The loading conditions were selected based on the results of previous tests conducted by Mohammad and Herath, 2005 on subgrade soils in Louisiana. The permanent deformation tests were performed on laboratory-molded samples that were cured for 7 days and 28 days prior to testing. It was also not possible to conduct single-stage permanent deformation tests on the raw soil specimens at high moisture contents.

3. Test results and analysis

3.1. Unconfined compressive strength

A series of UCS tests was conducted on the raw soil at different moisture contents. A typical variation in the average UCS of the raw soil with moisture contents is presented in Fig. 3. The average consisted of three specimens. This graph is important in the selection of the moisture content for preparing

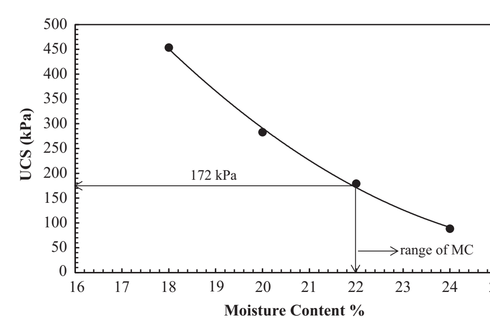

Fig. 3. Variation in UCS with moisture content for soil II.

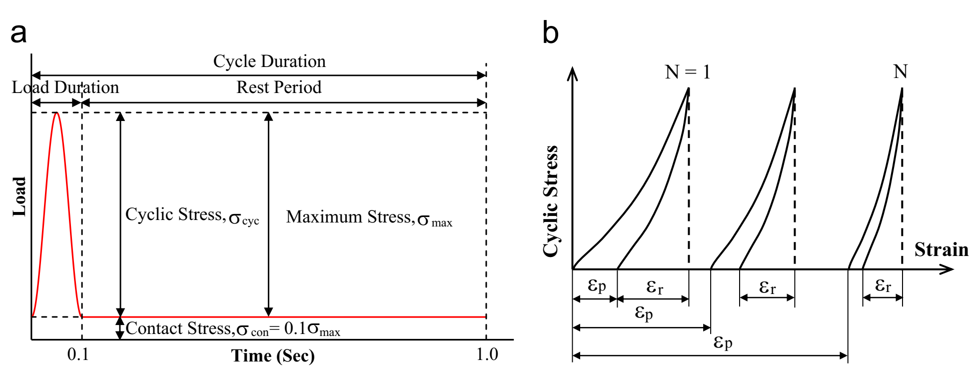

Fig. 2. Repeated load triaxial tests.

the samples for later UCS and RLT tests of the treated/stabilized-subgrade soils in this study. The set of three moisture contents, producing soil strength of 172 kPa (25 psi) or less (to represent very weak wet soils), for the five raw subgrade soils were chosen for treatment/stabilization and are summarized in Table 2.

The treated/stabilized-soil specimens were prepared by mixing the raw soils with different percentage of stabilizer (cement, lime or lime–cement) at the selected moisture contents, which produce a UCS of 172 kPa or less for the raw subgrade soils, as shown in Table 2. The 7-day UCS tests were then performed on these specimens to determine the percentage of stabilizer doses needed to achieve the target UCS values of 345 kPa (50 psi) and 1034 kPa (150 psi). For silty and sandy soils, the Louisiana experience indicated that cement works much better than lime. For high PI clayey soils, both lime and cement were tried, first individually, for the treatment/stabilization of the soil. While adding lime alone cannot bring the strength of the soil up to the target value, the cement alone did not improve the workability of the soil or its mixing characteristics significantly. As such, a combination of lime and cement (1:1) was selected to treat/stabilize high plasticity soils. Fig. 4 presents a typical variation in average UCS values at different combinations of stabilizer (cement here) and water content. Based on these results, the final stabilizer contents, which were rounded up to the nearest 1 percent, were selected for this study and are presented on Table 3.

The stress–strain behavior of the raw soil specimens were also compared with the treated/stabilized soil specimens prepared at the pre-selected moisture contents and additive contents, when possible, since it was not possible to test the raw soil samples at higher moisture contents. The addition of stabilizers enhances the strength and stiffness of the raw soils and, at the same time, the soil loses its ductile nature or cohesive nature and becomes more brittle as the axial strain decreases considerably due to the increase in additive contents. Typical stress–strain curves for soil specimens with different types of stabilizers are presented in Fig. 5. The figure clearly indicates that the stress–strain curves shift towards the left-hand side as the strain at failure decreases with the increase in stabilizer content and is associated with higher compressive strength, hence, increasing the elastic modulus and shear modulus of the treated/stabilized soils.

Table 2
Summary of selected working moisture contents.

Soil no.	Soil name	MC1 (%)	MC2 (%)	MC3 (%)
I	Low PI	14	17	20
II	Low PI	22	24	28
III	Medium PI	24	28	32
IV	High PI	31	35	39
V	Heavy clay	42	46	52

3.2. Resilient modulus tests

Extensive resilient modulus tests were performed in the laboratory using the MTS machine on the treated/stabilized soil specimens prepared at three different moisture contents, as

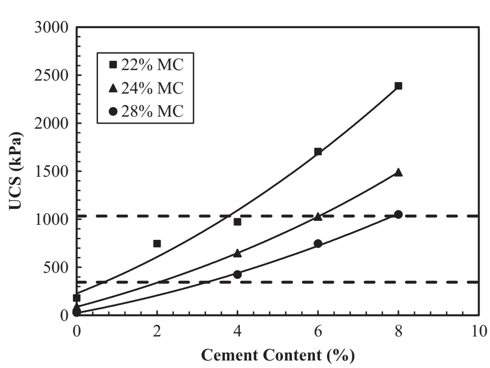

Fig. 4. Variation in UCS with cement content for soil II.

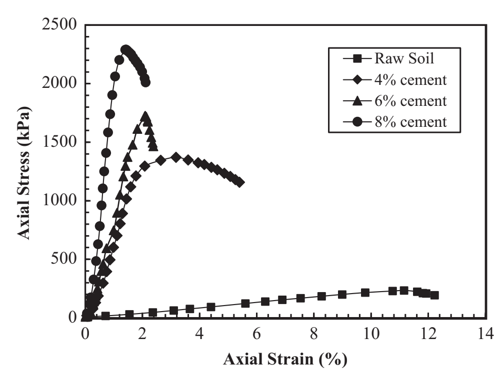

Fig. 5. Stress–strain relationships for soil III with and without cement (MC_1).

Table 3
Selected additive types and contents for different soils.

Soil no.	Soil type	MC1		MC2		MC3		Additive selected
		345 kPa (%)	1034 kPa (%)	345 kPa (%)	1034 kPa (%)	345 kPa (%)	1034 kPa (%)	
I	Low PI	0.5	1	1	2	2	3	Cement
II	Low PI	1	4	2	6	4	8	Cement
III	Medium PI	1	5	2	8	4	10	Cement
IV	High PI	2	6	3	8	4	10	Lime–cement
V	Heavy clay	3*	6	5*	8	7*	12	Lime–cement

*Lime only.
Lime–cement (1:1).

presented in Table 2, and stabilizer contents, according to Table 3. Since the raw soil samples were too wet and weak, only the performance of the treated/stabilized soil samples cured at 7 days or 28 days were observed and included in the analysis. Among the various factors affecting the resilient response of the soil, the effects of factors like the stress state, the water/stabilizer ratio, and the plasticity index were studied and are discussed here.

The resilient modulus is a key input material property in pavement design. Different types of models have been developed to estimate the resilient modulus (e.g., Uzan, 1985; ARA, 2004; Ooi et al., 2004). These models account for the effects of both external confinement and shear stress on the resilient properties. Although all the models were developed for granular and cohesive soils, they have also been used by various researchers for estimating the resilient modulus of cementitiously treated/stabilized soil (Solanki et al., 2010). Among all the models available in the literature, the following model recommended by the AASHTO MEPDG (ARA, 2004) will be considered in this study for cementitiously treated/stabilized soils:

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(1 + \frac{\tau_{oct}}{p_a}\right)^{k_3} \tag{6}$$

where θ is the bulk stress $= \sigma_1 + \sigma_2 + \sigma_3$; τ_{oct} is the octahedral shear stress $= [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}/3$; σ_1, σ_2, and σ_3 are the major, intermediate, and minor principal stresses, respectively; p_a is atmospheric pressure; and k_1, k_2, and k_3 are model constants.

Table 4 presents the average model constants (k_1, k_2, and k_3) obtained for the different soils. The average consisted of two specimens. These values can be used for pavement design and analysis provided that the state of stress is known from the layered elastic analysis, the finite element analysis, or any other means. The k_2 coefficient describes the stiffening (higher modulus) of the material with the increase in bulk stress. It is noted from Table 4 that all k_2 coefficients were less than 1. This indicates that the effect of bulk stress decreases with an increasing magnitude. Table 4 shows that all k_3 coefficients were negative. This is to be expected since this parameter describes the weakening of the material (lower modulus) with the increase in shear stress. Table 4 also shows that the magnitude of regression coefficients k_1, k_2, and k_3 is largely dependent on the soil type and the water/stabilizer ratio. This suggests that the specimens have similar UCS, but that different water/cement or water/stabilizer ratios show different resilient characteristics. As such, the use of a direct correlation between the UCS and the resilient modulus for cementitiously treated/stabilized soils can be misleading and should be carefully used in pavement design.

3.2.1. *Effect of stress state*

The typical variations in the resilient modulus, with stress conditions obtained from the laboratory tests of treated/stabilized specimens, are presented in Fig. 6. From the slope of the curves, it can be inferred that the effect of deviatoric stress is more pronounced in the lower deviatoric/cyclic stress level of application irrespective of the confining stress, and becomes less effective as

Table 4
Model constants for different soils.

Soil no.	Model constant	7 Days					
		345 kPa target (7-day UCS)			1034 kPa target (7-day UCS)		
		MC1	MC2	MC3	MC1	MC2	MC3
I	k_1	557.07	447.53	2201.67	1138.30	2323.61	3885.64
	k_2	0.53	0.34	0.60	0.86	0.93	0.81
	k_3	−1.81	−1.47	−2.10	−3.41	−2.38	−1.58
II	k_1	407.97	997.79	1590.34	1794.36	2041.80	2820.23
	k_2	0.57	0.59	0.45	0.75	0.91	0.50
	k_3	−3.51	−3.83	−2.13	−1.76	−1.83	−2.17
III	k_1	292.21	997.81	1647.85	1778.82	2018.38	2299.41
	k_2	0.22	0.59	0.42	0.61	0.68	0.70
	k_3	−1.68	−3.83	−1.72	−1.69	−1.82	−1.54
IV	k_1	997.00	897.49	823.40	1649.44	1247.30	1607.96
	k_2	0.43	0.50	0.44	0.81	0.79	0.80
	k_3	−2.80	−3.27	−3.26	−2.23	−1.79	−1.94
V	k_1	708.03	587.30	749.81	1764.29	1328.38	1392.22
	k_2	0.24	0.46	0.57	0.43	0.55	0.62
	k_3	−1.88	−2.73	−2.31	−1.59	−1.99	−2.72
		28 Days					
II	k_1	325.79	982.66	1555.64	1965.53	2169.57	2450.63
	k_2	0.30	0.62	0.75	0.94	0.97	0.48
	k_3	−2.32	−3.82	−2.59	−2.80	−2.94	−1.80
V	k_1	670.42	665.10	706.17	1810.49	1642.19	1740.75
	k_2	0.38	0.48	0.60	0.48	0.84	0.70
	k_3	−2.07	−2.32	−2.11	−1.33	−2.03	−1.96

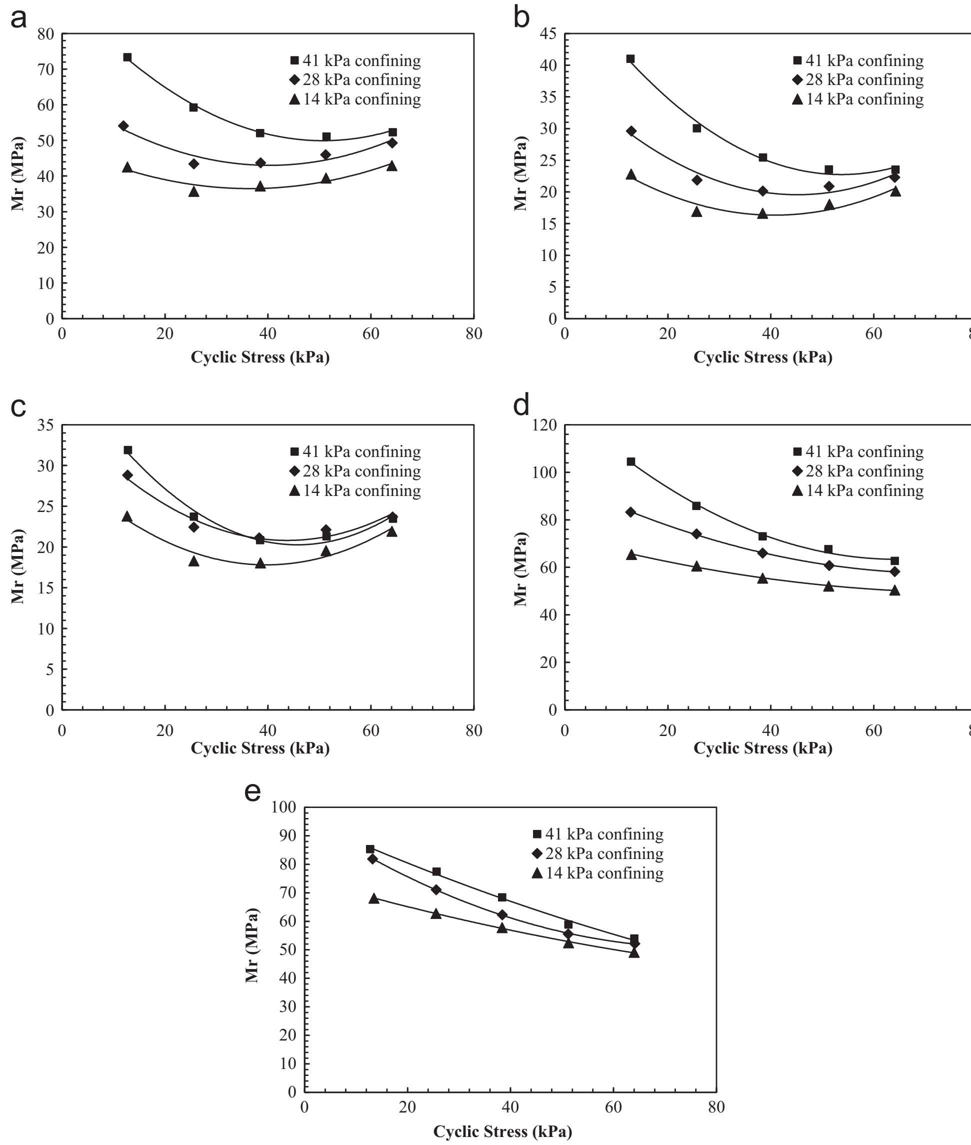

Fig. 6. Resilient modulus of treated soil specimens [MC = MC_1 and UCS = 345 kPa (50 psi)].

the curves attain a slope of almost zero after certain level of deviatoric stress. This type of behavior represents strain softening to subgrade materials under an increasing deviatoric/cyclic stress. Furthermore, as expected, the confining stress has a positive effect on the resilient modulus, such that an increase in the resilient modulus was observed with the increase in confining stress.

3.2.2. Effect of plasticity

Fig. 7 presents a comparison of the resilient modulus with PI variations obtained for different soil types that were treated/stabilized to reach the same target UCS. It should be noted here that to achieve the same target UCS, a higher stabilizer content is added with a higher moisture content, as shown in Table 3. The general trend shows that for similar UCS, the resilient moduli of low to Medium PI soils (I, II, and III) increases with an increasing cement content regardless of the moisture content. In contrast, for high PI soils (IV and V) treated with lime/lime–cement, the resilient moduli of the specimens were a little higher at a combination of lower stabilizer content and lower moisture content. Finally, at a moisture content of MC_3, the performance of the soils decreases with the increase in PI for same target UCS.

3.2.3. Effect of water/stabilizer ratio

The effect of various combinations of water to stabilizer ratios on the resilient modulus for the five different soil types was observed for the curing period of 7 days. In the case of cement-treated/stabilized soil samples (soil I, soil II, and soil III), having similar UCS, the test results showed a decrease in resilient modulus with an increase in the water/cement ratio (Fig. 8a) and vice versa. One explanation for this behavior may be partially due to the increase in capillary pressure (suction) as the saturation decreases; hence, the material stiffens as the capillary pressure increases. It should be noted here that an increase in the resilient modulus for the tested specimens in this study is also associated with an increase in the cement content, as shown in Fig. 9. This means the viability of more

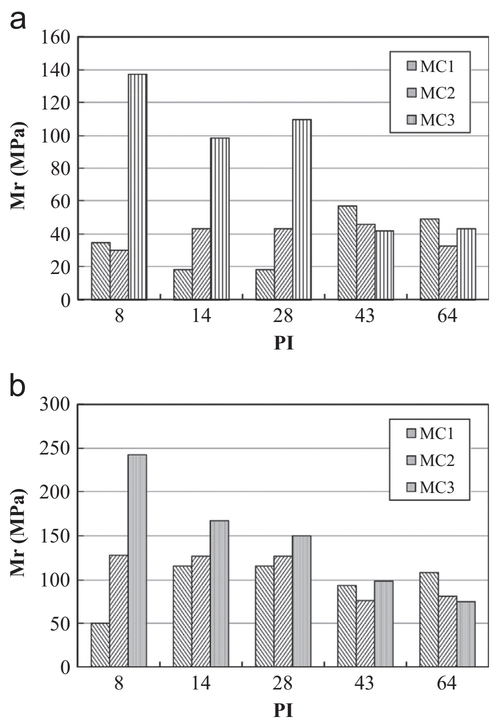

Fig. 7. Variation in resilient modulus with PI of soil. (a) UCS = 345 kPa (50 psi) and (b) UCS = 1,034 kPa (150 psi).

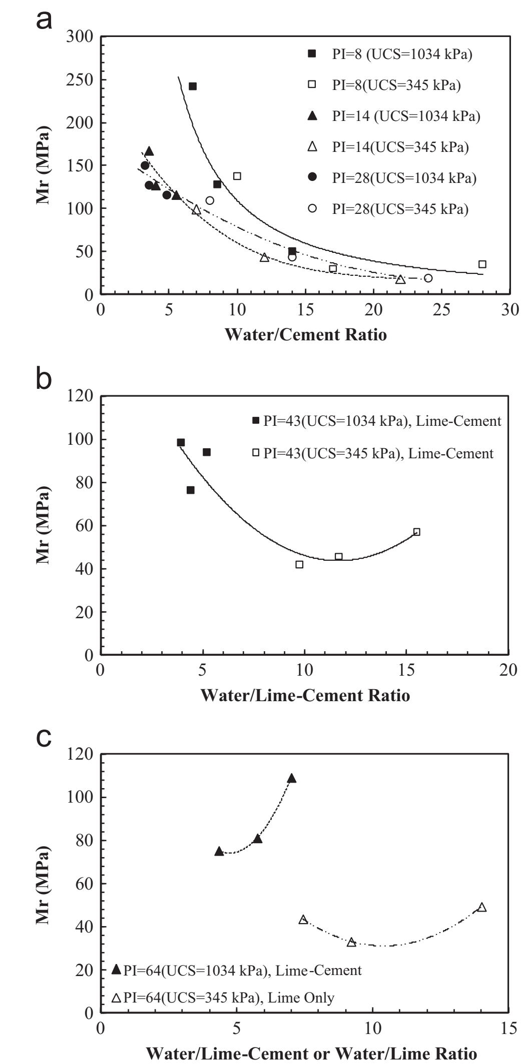

Fig. 8. Resilient modulus of treated soils at different water/stabilizer ratios.

calcium ions to exchange with monovalent cations present in the clay sample during the cation exchange process. Hence, the thickness of the diffused double layer decreases, the contact between the clay particles increases, and the material stiffens.

For soil IV, treated/stabilized with an equal proportion of lime and cement, it seems that the resilient modulus decreases with an increasing water/stabilizer ratio to a certain value, after which it increases slightly (Fig. 8b). However, contrary behavior was observed for soil V, treated/stabilized with both lime and cement at the target UCS of 1034 kPa (150 psi), in which higher resilient moduli were obtained at higher water/stabilizer ratios as compared to lower water/stabilizer ratios (Fig. 8c). Additionally, the lime-treated/stabilized soil V at the target UCS of 345 kPa (50 psi) shows similar behavior to the lime–cement treated/stabilized soil IV as the resilient modulus decreases with an increasing water/additive ratio to a certain value, then it increases slightly again (Fig. 8c). The different behaviors of the lime–cement treated/stabilized soils can be attributed to the different reaction mechanisms between lime and cement and the fact that cement is more effective in increasing M_r than lime. In short, cement stiffens the soil mainly through the hydration process, in which cementitious materials are formed to bind the soil particles together. Meanwhile, lime increases the stiffness of soil mainly through changes in the soil texture induced by the cation exchange.

3.2.4. *Effect of curing time*

Among the tested soils, two soils (soil II and soil V) were also cured for 28 days before testing in the MTS machine to evaluate the effect of curing time on the resilient modulus of the treated/stabilized specimens. For cement-treated/stabilized

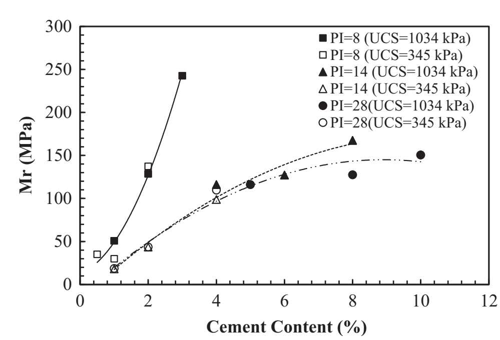

Fig. 9. Resilient modulus of treated soils at different cement contents.

soil II, the test results showed a slight decrease or no change in resilient modulus of the specimens tested after 28 days of curing as compared with the specimens cured for 7 days prior to testing (Fig. 10a). The drop in resilient modulus for the specimens after 28 days of curing may be due to drying-induced microcracking. Since the specimens were cured in airtight plastic bags, microcracking may have occurred during the self-desiccation (i.e., autogenous shrinkage), which is a

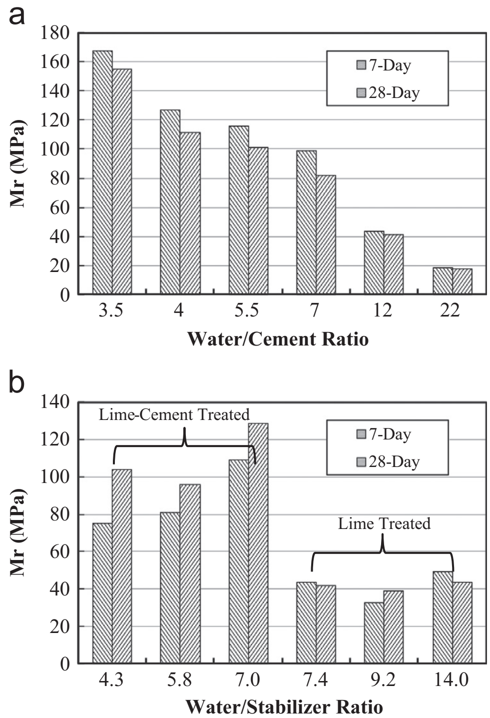

Fig. 10. Variation in resilient modulus with curing time. (a) Soil II and (b) Soil V.

process where physical and chemical changes in the cement components during hydration lead to the drying of the capillary pores in the soil–cement.

Fig. 10b presents the resilient modulus of soil V obtained at curing periods of 7 days and 28 days. The figure shows no significant change in the resilient modulus for lime-treated/stabilized soil V with curing time. However, for lime–cement-treated soil V, an increase in the resilient modulus was observed (up to +38%) after 28 days of curing as compared to the resilient modulus obtained after 7 days of curing. It seems that the presence of lime in combination with cement in the specimens enhances the gain in strength with time after 7 days of curing.

3.3. Permanent deformation

Repeated load triaxial tests were performed to evaluate the permanent (axial) deformation behavior of different treated/stabilized subgrade soil specimens. Fig. 11 presents the typical curves of the average permanent (axial) strain versus the number of cycles obtained for the different RLT cases. Averages consisted of two specimens. The permanent (axial) deformation curve has two distinct stages. In the first stage (post-compaction stage), the material accumulates a significant amount of permanent deformation. This is most probably due to the extra compaction and the initial particle bonding breakage induced by the particle re-arrangement. During the second stage (secondary stage), the material accumulates permanent strain at a much lower rate and, in some cases, the permanent deformation even approaches a constant value. The permanent (axial) strains observed for all the treated soil specimens after 10,000 cycles of loading are summarized in Table 5.

3.3.1. Effect of plastic index

Fig. 12 presents a comparison of the permanent deformation obtained for the different soil types treated/stabilized to reach the same target UCS. No definite relation was observed between the permanent deformation and the PI value. For the same soil, the permanent deformation decreases with an increase in the cement content regardless of the moisture content. However, the behavior is different for the lime- or lime–cement-treated/stabilized specimens, which show no trend. The figure also shows, for lightly treated subgrade soil of working table application, the permanent deformation is substantial, while for heavily treated subgrade soil for subbase applications, the permanent deformation is somehow negligible (permanent strain $<0.08\%$) and might be ignored in pavement design. This observation is consistent with the UCS test results, which show that the stress–strain curves shifted towards the left-hand side (brittle behavior) as the percent of stabilizer content increased (Fig. 5). This is also in agreement with the MEPDG, which does not consider the deformations of the cement-stabilized layers in pavement design.

3.3.2. Effect of water/stabilizer ratio

The effect of the water/stabilizer (cement, lime–cement, or lime) ratio on the permanent deformation behavior is presented in Fig. 13. The behavior of cement-treated soil specimens (soils I, II, and III) demonstrated clearly that the permanent strain increases with an increase in the water/cement ratio (Fig. 13a). This may be due to the decrease in capillary pressure (suction) with the increase in the water/cement ratio, as discussed earlier. It should be noted here that the decrease in water/cement ratio for the tested specimens in this study is associated with an increase in the cement content, i.e., permanent deformation also decreases with the increase in cement content regardless of the moisture content, as shown in Fig. 14. The behavior of the lime–cement-treated/stabilized soil specimens (soil IV) shows that the permanent deformation increases with an increasing the water/(lime–cement) ratio up to a maximum value, after which it decreases (Fig. 13b). Meanwhile, the permanent deformation of lime-treated soil specimens (soil V) decreases with an increasing water/lime ratio (Fig. 13c). It seems that the cement stabilizer is more effective in reducing the permanent deformation of soil specimens than the lime stabilizer.

3.3.3. Effect of curing time

Fig. 15 presents the permanent deformations obtained for soils II and V (UCS = 345 kPa) at curing periods of 7 days and 28 days. A significant decrease in permanent deformation (up to 96 percent) was observed for the specimens cured for 28 days as compared to those cured for 7 days. This difference can be attributed to the increased bond strength of the cementitious paste with time, resulting in less particle–bonding breakage for the specimens after 28 days of curing during the permanent deformation tests, and thus, less particle re-arrangement. It seems that while autogenous shrinkage-induced microcracking has a significant detrimental effect on the resilient modulus, as discussed earlier, its negative effect on permanent deformation is minimal. For cement-treated

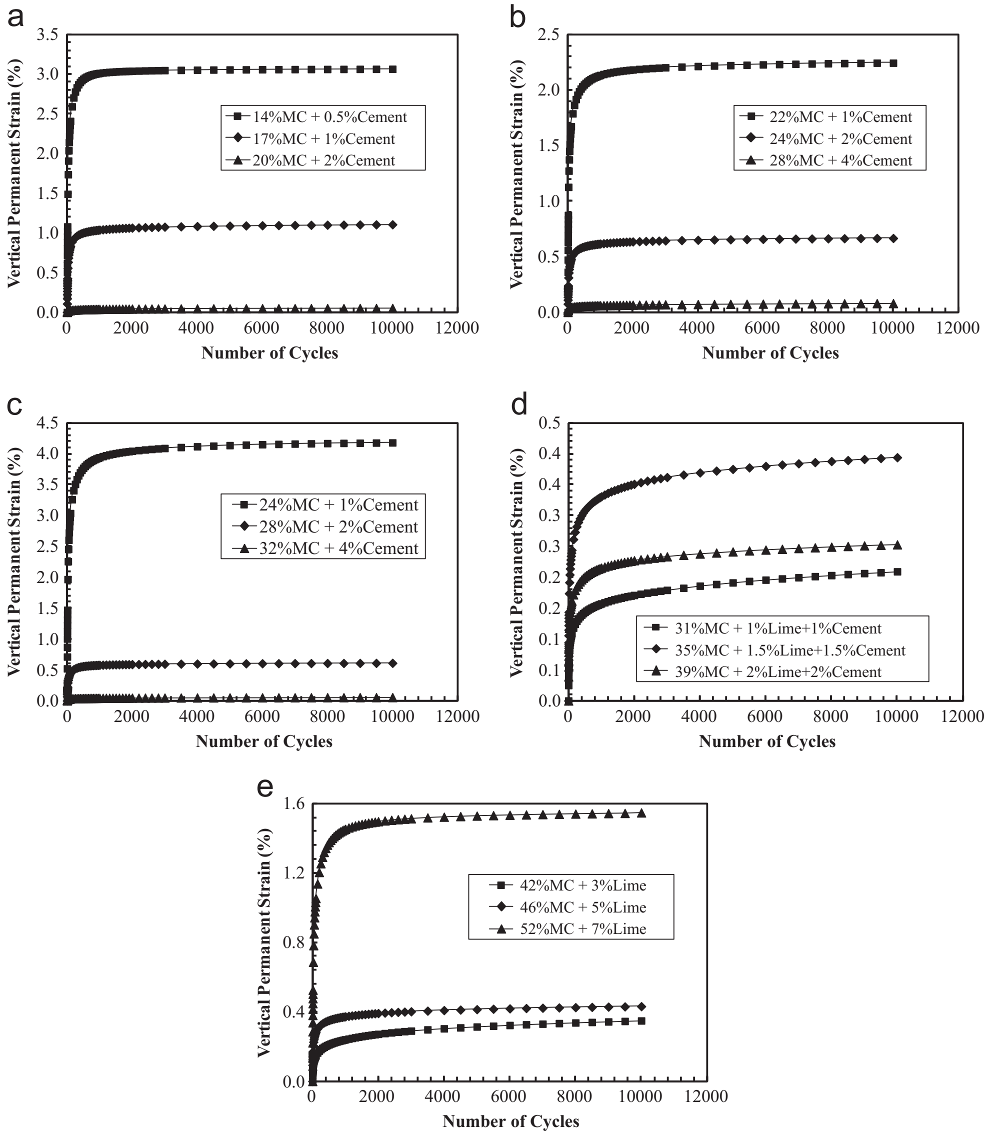

Fig. 11. Permanent deformation of treated soil specimens [UCS = 345 kPa (50 psi)]. (a) Soil, (b) Soil II, (c) Soil III, (d) Soil IV and (e) Soil V.

Table 5
Vertical permanent strain of specimens at 10,000th cycle.

Soil no.	7 Days					
	345 kPa target			1034 kPa target		
	MC1	MC2	MC3	MC1	MC2	MC3
I	3.065	1.107	0.051	0.395	0.027	0.033
II	2.244	0.666	0.080	0.032	0.076	0.030
III	4.182	0.610	0.054	0.043	0.032	0.020
IV	0.209	0.394	0.253	0.056	0.057	0.050
V	0.349	0.431	1.548	0.058	0.046	0.062
	28 Days					
II	0.754	0.438	0.047	0.032	0.073	0.016
V	0.342	0.158	0.056	0.042	0.025	0.020

soil II, the percent reduction in permanent deformation increases with an increasing water/cement ratio (Fig. 15a), which is associated with a decrease in the cement content. For lime- or lime–cement-treated soil V, on the other hand, the percent reduction in permanent deformation decreases with an increasing water/stabilizer ratio (Fig. 15b).

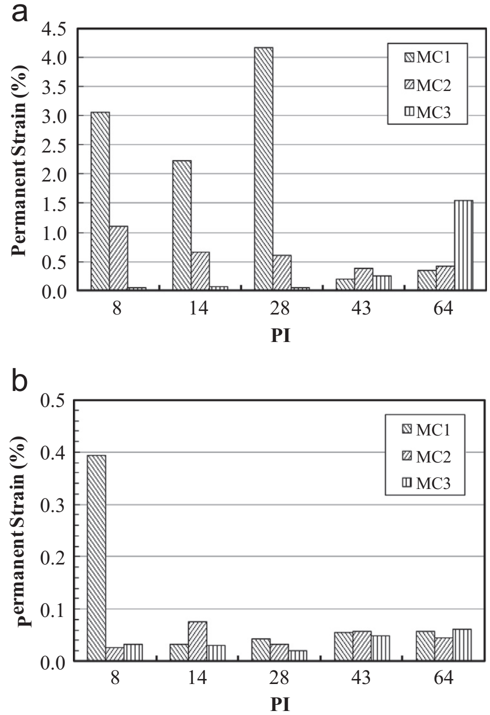

Fig. 12. Variation in permanent deformation with PI of soil. (a) UCS = 345 kPa (50 psi) and (b) UCS = 1034 kPa (150 psi).

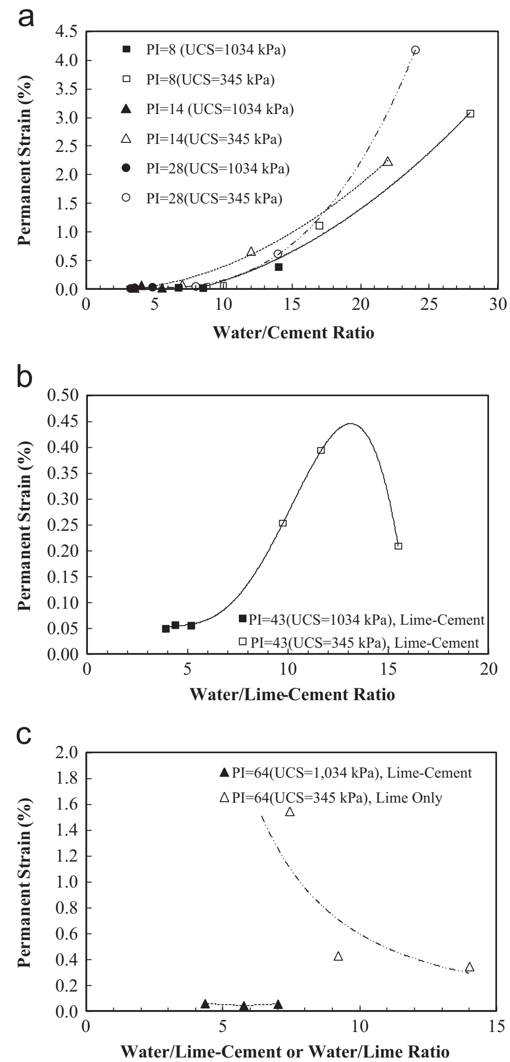

Fig. 13. Permanent deformation of treated soils at different water/stabilizer ratios.

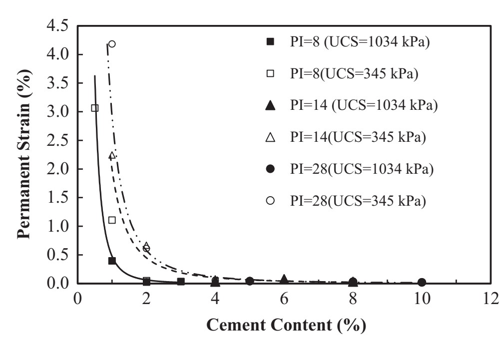

Fig. 14. Permanent deformation of treated soils at different cement contents.

4. Summary and conclusions

The performance-related properties (e.g., resilient modulus and permanent deformation) of cementitiously treated/stabilized very weak subgrade soils were evaluated in this study. Five different soils that represent the typical range in subgrade soils in Louisiana were studied. Three different wet of optimum moisture contents, producing a raw soil strength of 172 kPa (25 psi) or less (representing very weak soils), were chosen for treatment/stabilization. The percentage of cementitious stabilizer was determined to achieve the target 7-day strength values of 345 kPa (50 psi) (for working table applications) and 1034 kPa (150 psi) (for subbase applications). Based on the results of this research study, the following conclusions can be drawn:

- The proper selection of stabilizer content (cement, lime, or lime–cement) for very weak and wet subgrade soils can substantially improve their performance in terms of the resilient modulus and the permanent deformation for working table and subbase applications.
- Lime was sufficient for treating high plasticity soils for working table applications, whereas a combination of lime and cement was needed to stabilize high plasticity soils for subbase applications. Cement worked better for silty and sandy soils than lime.
- The mechanical behavior of soil dramatically changed from ductile-like to brittle-like when the cementitious stabilizer was added. Additionally, the soil became stiffer and the compressive strength increased with the increase in stabilizer content.
- The use of a direct correlation between the UCS and the resilient modulus for the cementitiously stabilized soils can be misleading. From the findings of this study, it can be inferred that specimens having similar UCS, but different water/cement or water/stabilizer ratios have shown different resilient characteristics.
- The resilient modulus and permanent deformations were found to be a function of the water to cement ratio, such that the resilient modulus increases and the permanent deformation dec-

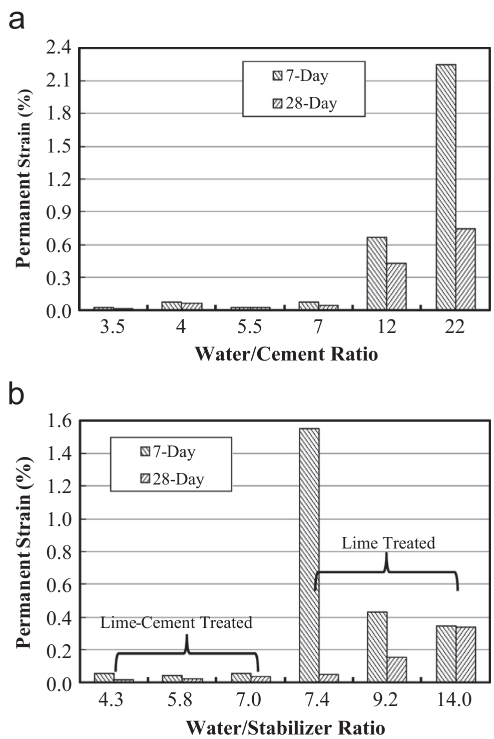

Fig. 15. Variation in permanent deformation with curing time. (a) Soil II and (a) Soil V.

reases with a decrease in the water/cement ratio. However, it was difficult to identify the effect of the water to lime (or lime–cement) ratio on the soil characteristics under repeated loading.

- As expected, the observed resilient moduli were higher for higher confining stresses and decreased with an increase in the deviatoric stress under identical confinement, representing strain-softening behavior.
- In the case of cement-treated soil, specimens tested after a curing period of 28 days showed a lower resilient modulus than specimens tested after a curing period of 7 days. However, the soil treated with the combination of lime and cement showed a significant increase in resilient modulus with an increase in the curing period.
- In the case of permanent deformation, no matter which type of stabilizer was used, all specimens showed a decrease in permanent deformation with an increase in the curing period.
- For heavily stabilized subgrade soil for subbase applications, the permanent deformation is somehow negligible (permanent strain $<0.08\%$) and thus, it can be ignored in pavement design.

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